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INFLUENCE OF Ge ISOVALENT IMPURITY ON ANISOTROPIC PARAMETERS OF n-Si SINGLE CRYSTALS

The summary. *The paper presents results of influence Ge Isovalent Impurity on anisotropic parameters of* n-Si *single crystals. The experimental results for investigated single crystals are shown that introduction Ge Isovalent Impurity into n-Si significantly reduce relaxation time $<\tau_\perp>$ and electron mobility $\mu_\perp$; brings to a reduction piezoresistance effect. Increasing of Ge Isovalent Impurity is changing the corresponding anisotropy parameters. Electron collision with Isovalent Impurity is close to isotropy scattering. Zone characteristic of single crystals n-Si with Ge Isovalent Impurity doesn't change up to $N_{Ge} \leq 20 \cdot 10^{19}$ cm^{-3}.*

Key words: *isovalent impurity, piezoresistance, single crystal, relaxation time, electron mobility parameter of relaxation times anisotropy.*

С. Місюк

ВПЛИВ ІЗОВАЛЕНТНОЇ ДОМІШКИ Ge НА АНІЗОТРОПНІ ПАРАМЕТРИ КРИСТАЛІВ n-Si

Резюме. *Представлено результати досліджень впливу ізовалентної домішки Ge на анізотропні параметри кристалів n-Si. Експериментальні результати для досліджених кристалів показали, що введеня ізовалентної домішки Ge в кристали n-Si суттєво зменшує час релаксації $<\tau_\perp>$, рухливість електронів $\mu_\perp$ та призводить до зменшення п'єзопору. Розсіювання електронів ізовалентними домішками германію є близьким до ізотропного. Зонні характеристики кристалів n-Si з умістом ізовалентної дмішки Ge з концентрацією $N_{Ge} \leq 20 \cdot 10^{19}$ cm^{-3} не змінюються.*

Ключові слова: *ізовалентна домішка, п'єзоопір, кристал, час релаксації, рухливість електронів, параметр анізотропії часів релаксації.*

Introduction. Modern engineering development demands the new materials investigations. That's why n-Si single crystals with Ge Isovalent Impurity (GeII) investigations are very actual [1]. Inner local stresses arise during doping silicon crystals by germanium atoms as a result of difference between the covalent radius of Si (1.17 Å) and Ge isovalent impurity, deforming the crystal lattice, changing its constant and, thus, influencing upon electrophysical and anisotropic properties of the crystal [2].

Objective. This paper presents results of piezo-resistanse effects and anisotropic parameters investigations of in n-Si single crystals with GeII with concentrations of Germanium $N_{Ge}=2\cdot10^{19}\div20\cdot10^{19}$cm^{-3}. The investigated crystals were grown by Chokhralsky method with oxygen content ~10^{17}cm^{-3}. The control samples without GeII were performed for comparison.

Results and discussion. Crystals of n-Si manifest maximal piezosensitivity in case when current J and stress P are directed along [100], that is $P\|J\|[100]$. Figure 1 presents the dependencies of longitudinal piezoresistance on pressure $P\|J\|[100]$ at temperatures T=77K and T=300K. The common feature of plots $\rho_P/\rho_0=f(P)$ is the decrease of piezoresistance coupled with the increase of GeII concentration. As tensoeffect is caused by anisotropy of the crystal, the presented results testify to the fact that doping the crystal with isovalent impurity changes the corresponding anisotropy parameters.

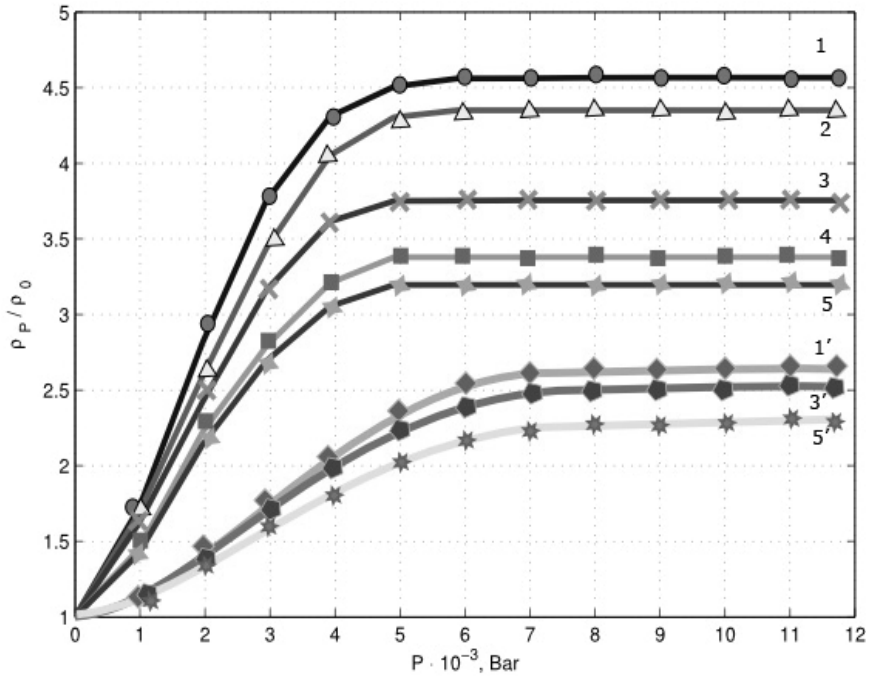

Figure 1. Longitudinal piezoresistance of n-Si crystals and n-Si with different content of GeII for the case $P \parallel J \parallel [100]$ at T=77K [3]: 1 – n-Si without GeII, 2 – n-Si with $N_{Ge}=2\cdot10^{19}$cm^{-3}. 3 – n-Si with $N_{Ge}=4\cdot10^{19}$cm^{-3}, 4 – n-Si with $N_{Ge}=7\cdot10^{19}$cm^{-3}, 5 – n-Si with $N_{Ge}=20\cdot10^{19}$cm^{-3} and T=300K: 1' - n-Si without GeII, 3' - n-Si with $N_{Ge}=4\cdot10^{19}$cm^{-3}, 5' – n-Si with $N_{Ge}=20\cdot10^{19}$cm^{-3}

For crystals of n-Si piezoresistance $\rho_P/\rho_0=f(P)$, which is brought about at P||J||[100] is determined as [4]:

$$\rho_P = \rho_0 \frac{(1+2C)(1+2K)}{3(1+2C)}, \tag{1}$$

$$C = \frac{n_2}{n_1} = e^{-\frac{\Delta E}{kT}}, \tag{2}$$

where n_1 is the concentration of current carriers in lowering ellipsoids, n_2 is the concentration of current carriers in rising ellipsoids, K is the parameter of mobility anisotropy [4]:

$$K = \frac{3}{2}\frac{\rho_\infty^{[100]}}{\rho_0} - \frac{1}{2}, \tag{3}$$

Thus, the dependence $\rho_P=f(P)$ can be determined by expression (1) and experimental data of ρ_0 and $\rho_\infty^{[100]}$.

For deformations which afford the complete migration of the carriers into energy minima, we may write:

$$\frac{1}{\rho_\infty^{[100]}} = en\mu_{\parallel}, \tag{4}$$

where n is a carriers concentration, $\mu_{\parallel}$ is a current carriers mobility along the main axis of ellipsoid.

As it is known, the parameter of mobility anisotropy is [4]:

$$K = \frac{\mu_{\perp}}{\mu_{//}}, \tag{5}$$

where $\mu_{\perp}$ is the current carriers mobility in perpendicular to the main axis of ellipsoid direction.

The parameter of mobility anisotropy K can be defined from experimental data (Figure 1). In accordance to (3) and usage the expression (5) let's plot a dependence $\mu_{\perp}=f(N_{Ge})$. It is shown on Figure 2.

Magnitude $\mu_{||}$ characterizes the mobility along the main axis of isoenergetic ellipsoid. For $\mu_{||}$:

$$\mu_{||} = \frac{e}{m_{||}}\langle \tau_{||} \rangle, \tag{6}$$

where $m_{||}$ is a longitudinal component of effective masses tensor, $<\tau_{||}>$ is a relaxation time along the main axis of ellipsoid.

The analysis of the obtained results shows that $\mu_{||}$ practically does not depend (accurate up to 4%) on the concentration of isovalent impurity. So, $<\tau_{||}>$ also practically does not change.

Let us consider the expression for $\mu_{\perp}$:

$$\mu_{\perp} = \frac{e}{m_{\perp}}\langle \tau_{\perp} \rangle, \tag{7}$$

where $m_{\perp}$ is a transversal component of effective masses tensor, $<\tau_{\perp}>$ is relaxation time transversal to the leading axis of ellipsoid.

As can be seen from Figure 2 $\mu_{\perp}$ sufficiently depends on the GeII content in n-Si. There are grounds to consider that such behavior of $\mu_{||}$, $\mu_{\perp}$ and, hence, times of relaxation $<\tau_{||}>$, $<\tau_{\perp}>$ is provoked by corresponding effective masses $m_{||}$, $m_{\perp}$. It was determined by method of cyclotron resonance that $m_{||}=0.9163m_0$ and $m_{\perp}=0.1905m_0$ [4]. So, we may affirm that mass $m_{||}$ is more "inert" to various changes in the crystal and, therefore, $<\tau_{||}>$ practically does not change. As to $m_{\perp}$, it is about one fifth as large as $m_{||}$ and, therefore, its perpendicular component is more "sensitive" to various influences. So, time $<\tau_{\perp}>$, describing pulse relaxation for $m_{\perp}$, will change more substantially than $<\tau_{||}>$, which has been confirmed by the experiment.

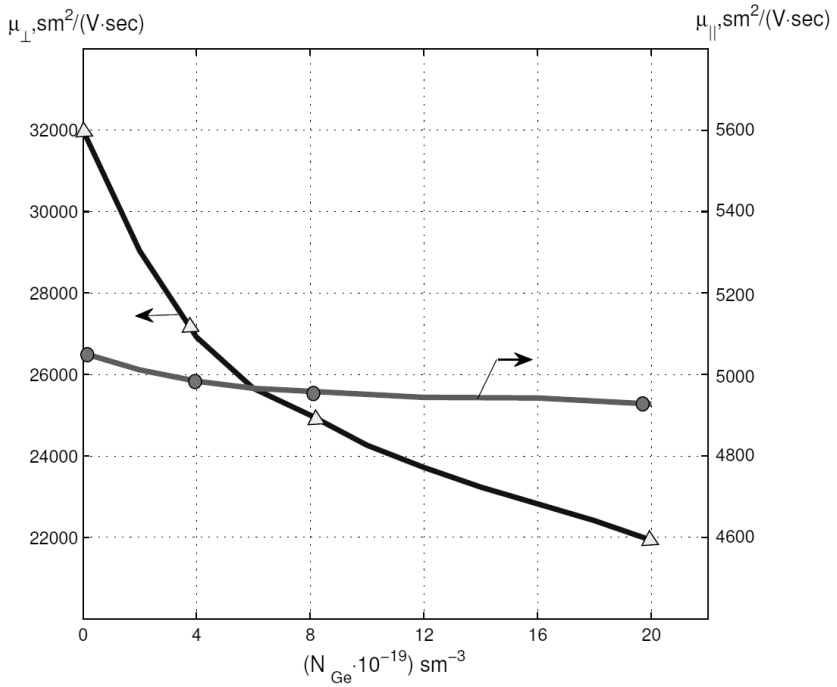

Figure 2. $\mu_{\perp}=f(N_{Ge})$, $\mu_{||}=f(N_{Ge})$ dependences for n-Si crystals with different content of GeII

Plots 1-5 on Fig. 1 furnish to determine the parameter of relaxation times anisotropy as:

$$K_{\tau}=\frac{K}{K_m}, \tag{8}$$

where $K_{\tau}=\frac{\langle\tau_{||}\rangle}{\langle\tau_{\perp}\rangle}$, $K_m\frac{m_{||}}{m_{\perp}}=4.81$.

Values of K and K_{τ} for n-Si crystals without GeII agree with paper data [4]. Figure 3 shows K_{τ} dependence on GeII concentration. The graph of parameter K_{τ} tends to 1 with the increase of N_{Ge}. The obtained result shows that scattering on GeII in silicon crystals is rather close to isotropic one.

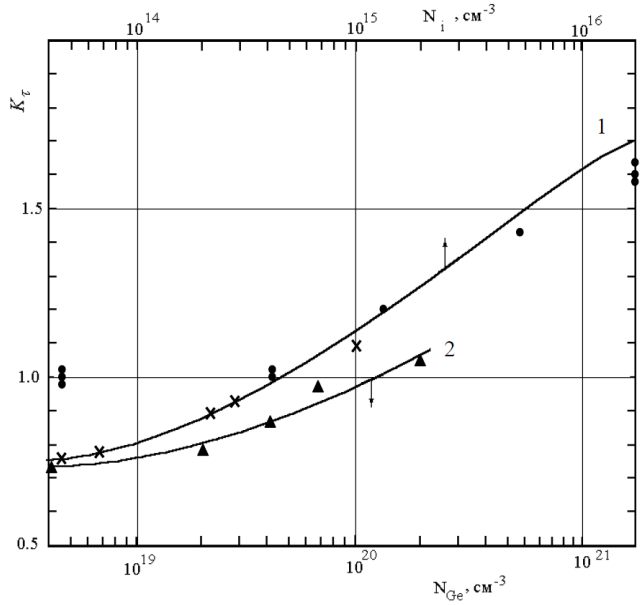

Figure 3. Dependence $K_{\tau}=f(N_{Ge})$ for n-Si crystals with different content of GeII. 1 – theoretical curve by taking into account of anisotropy scattering on ionized donors [4], ×● - experimental data from [4,5]; 2 – (▲) experimental data for investigated crystals

Usage experimental data (Figure 1) we may determine the constant of deformation potential Ξ_u for n-Si crystals with different concentration of GeII. For temperature T=77K we have [6]:

$$\Xi_U = 1.63 \cdot 10^4 \frac{\lg\left(C \cdot 10^4\right)}{P}, \tag{9}$$

where C is determined from (2), P is expressed in Bar.

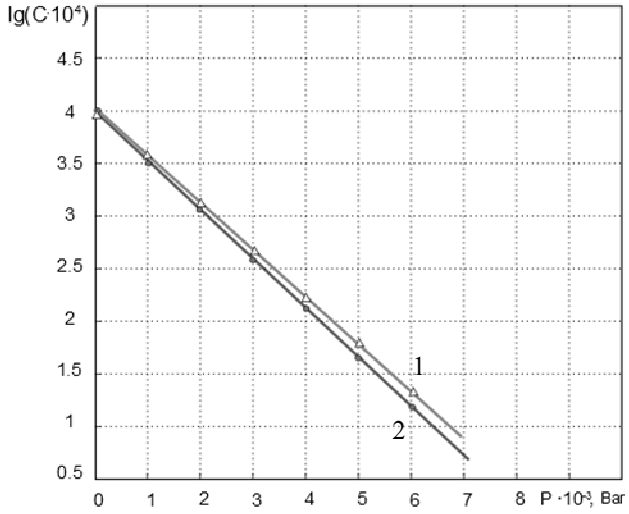

Figure 4. Dependences *lg(C·10⁴)=f(P) for determination of* Ξ_u - constants of deformation potential: 1 - n-Si with $N_{Ge}=20\cdot10^{19}$cm^{-3} ; 2 – for crystals – n-Si without GeII, and with $N_{Ge}\leq7\cdot10^{19}$cm^{-3}

Thus, in the case of the dominating contribution of the electrons inter-valley redistribution mechanism to the piezoresistance we obtain a linear dependence *lg(C·10⁴)=f(P)* (Figure 4). We find the constant of deformation potential Ξ_u=9.3eV from the slopes of dependences for pure n-Si and for crystals with GeII up to $N_{Ge}=7\cdot10^{19}$cm^{-3}. The decrease of deformation potential constant down to Ξ_u=9.0eV is observed for concentration $N_{Ge}=20\cdot10^{19}$cm^{-3}. The obtained data testify to the fact that band and elastic characteristics of n-Si with GeII do not practically change at concentrations $N_{Ge}\leq20\cdot10^{19}$cm^{-3}.

Conclusions. Summarizing our investigations of inisotropic parameters and uniaxial piezoresistanse for n-Si with GeII we can make the following conclusions:

- introduction GeII into n-Si crystals actually don't influence on the values of $<\tau_{\|}>$ and $\mu_{\|}$, but significantly reduce $<\tau_{\perp}>$ and $\mu_{\perp}$. This reduction can be justified because the increasing of Ge concentration reduces quantity of the scattering centres and therefore increases the probability of impulse scattering. Herewith electron moves faster in equilibrium, and therefore the corresponding relaxation time decreases.
- introduction GeII into n-Si crystals brings to a reduction piezoresistance effect;
- increasing of GeII is changing the corresponding anisotropy parameters;
- electron collision with isovalent impurity is close to isotropy scattering;
- zone characteristic of investigated crystals doesn't change up to GeII $N_{Ge}\leq20\cdot10^{19}$cm^{-3}.

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